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ESTIMATES OF RADFORD AAP 31 MAY 1974 ACCIDENT EXPLOSIVE YIELD AND POTENTIAL TO AVOID DAMAGE BY USE OF SUPPRESSIVE STRUCTURES

Donald F. Haskell

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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In this study, observed damage at the site and two independent analysis methods were used to estimate the explosive yield of the 31 May 1974 Radford Army Ammunition Plant TNT nitration and purification building accident. Results of these analyses indicate the explosive yield was equivalent to 8600 pounds of TNT. Based on this yield, if the building in which the accident occurred had been of the suppressive structure-type design, it is estimated that from 30% to at least 64% of the cost of the destruction at Radford could have been avoided.

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20. ABSTRACT (CONTINUED)

Further, use of suppressive structure-type design at all three of the Radford TNT nitration and purification buildings could have increased the potential cost savings to between 62% and 84% of the damage incurred by the 31 May 1974 accident.

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I. INTRODUCTION

At 1630 hours on 31 May 1974 an accidental explosion occurred at building 9502 within the TNT manufacturing facility of the Radford Army Ammunition Plant (RAAP), Radford, Virginia. This accident caused considerable damage to the TNT manufacturing facility. Before the accident, building 9502 was the A line nitration and purification building of a three line (A, B, C) continuous nitration and purification process used to produce trinitrotoluene. This was a prototype installation and the first facility built in this country for the continuous manufacture of TNT.

The purpose of this study, requested by the Mechanical Process Technology Division, Manufacturing Technology Directorate, Edgewood Arsenal, was to estimate the yield of the explosion and the amount of damage that could have been avoided if the A line nitration and purification building design had been of the suppressive structure type.

Structural blast damage information gathered at an on-site survey conducted on 3-4 December 1974 of the RAAP TNT Manufacturing Facility was combined with available concrete-block wall blast damage information, a knowledge of blast pressure variation with distance from an explosion, and the mechanics of structural deformation to arrive at the TNT explosive yield. In addition, predictions of the blast pressure field that would result from explosions within suppressive structure type nitration and purification buildings were made. These predictions were made for a range of levels of blast suppression. Estimates of the damage to the RAAP facilities caused by these pressure fields were, in turn, combined with available cost estimates of the actual RAAP damage to estimate the potential reduction in damage costs achievable with suppressive structures. These estimates were made for accidents of the same TNT yield as calculated herein for the RAAP accident, as well as lower and higher yields to uncover and display trends.

II. BACKGROUND

The RAAP TNT Manufacturing Facility is about 1300 feet wide by 2200 feet long and is roughly situated in the valley between two ridges some 120 feet high oriented approximately in the Northeast-Southwest direction. The three Nitration and Purification (N and P) buildings of lines A, B and C are located in a line that runs along the valley floor. Figure 1 is a layout of the TNT area. For clarity, only the more prominent structures are shown. The valley floor slopes gently downward approximately in the Northeast direction from C line to A line at a drop of about 3 feet per 100 feet along the horizontal. This TNT area is located within the Radford Manufacturing Unit of the Radford Army Ammunition Plant. This Radford Manufacturing Unit covers some 4154 acres.

Each line of the three line TNT manufacturing facility consisted of two buildings located about 210 feet apart: a Nitration and Purification Building and a Finishing Building. The TNT was manufactured in the N and P building by the continuous-flow process. The output, a hot molten TNT slurry containing some water, was pumped to the Finishing House where it was dried, flaked, and packaged for shipment.

The N and P buildings were approximately 55 feet wide and 62 feet long with three floors: an operating floor, basement floor, and pit floor. Overall height from pit floor to roof was about 30 feet: 11 feet between roof and operating floor, 8 feet between operating and basement floors, and 11 feet between basement and pit floors. The walls were conventional reinforced concrete, designed as retaining walls to support the exterior earth mounding which acted as a revetment around the four walls. The roof was corrugated metal and the floors were conventional reinforced concrete. All support structures were of conventional design with no provisions for resistance of explosive forces, Reference 1. The N and P buildings each contained the following process vessels: each contained eight nitrators, seven separators, an acid washer, two Sellite washers, two Sellite separators, a Sellite dissolver, a post Sellite washer, and a TNT pump tank all closely coupled into a continuous-flow process. This equipment was arranged along three walls of the building with a control console located at the center of the operating, or top, floor. Nitration occurred along two of the walls with the purification process located along the third wall. In addition, scrap TNT from other operations was stored in a remelt room in each of the N and P buildings.

The TNT manufacturing process consists of combining toluene and nitric acid to form the trinitrotoluene molecule. In the continuous process employed at Radford, toluene nitration is increased gradually as the process material is passed from the first nitrator to the last. In this manner the amount of TNT in the nitration process material is increased from the DNT state until at the last nitrator, the output is 100% TNT. The typical amounts of explosive contained in the N and P buildings are discussed in the following. The typical amount of TNT in the nitrators increased from some 20 odd pounds in the first couple of vessels to about 2000 lbs in the last two nitrators. TNT weights in the separators ranged from about 90 lbs in the first two separators to between about 480 to 540 lbs in the last three separators. The total quantity of TNT in the nitration process is 10,000 lbs. In addition to the TNT, DNT is present in the nitration process up to the seventh

[1] Letter to Commander, US Army Armament Command, ATTN: AMSAR-OP (Colonel Bailey) Rock Island, Illinois, 61201, NAOEN-D (20 June 1974) 1st Incl, Subject: Request for Structural Analysis of Explosion Damage to Radford Army Ammunition Plant TNT Area, from DA, Norfolk District, Corps of Engineers, Norfolk, Virginia, 31 July 1974.

nitrator. The amount of DNT present is about 4,000 lbs. The total quantity of TNT in the purification process is 4,600 lbs. This is typically distributed in the process vessels as follows: acid washer - 1300 lbs, Sellite washer - 900 lbs each, post Sellite washer - 1300 lbs, and TNT pump tank - 200 lbs.

III. DETERMINATION OF EXPLOSIVE YIELD

A. General

The procedure employed in this study to determine the TNT yield of the 31 May 1974 RAAP accident consisted of relating measured blast damage of selected structures to TNT yield through a knowledge of blast pressure decay with distance from an explosion as well as the mechanics of deformation of the selected damaged structures. To gather the needed damage information, a trip was made to RAAP for an on-site inspection. This inspection revealed three structures with quantifiable damage. These structures with the desired quantifiable blast damage were: a concrete block utility house (building number A9500) that served the "C" line N and P building, a trailer located next to the chemical storage house (building 9511) and a small, pre-engineered aluminum alloy building located near the toulene unloading station (building 9522) and the oleum unloading station (building 9516). Figure 1 shows the location of these objects relative to the explosion site at the "A" line N and P building. The concrete block utility house was located 560 feet Southeast from, and at an elevation of 17 feet above, the "A" line building. Both the trailer and the small, pre-engineered metal building were Northeast of "A" line at distances of 438 feet and 840 feet, respectively.

The wall of the utility house that had faced the explosion site at A line was shattered. This wall was approximately normal to A line. About half of a second wall was shattered. The remaining two walls were left relatively intact. Damage to the trailer consisted of general inward permanent deformation of the panels on the side that faced the explosion - this side was normal to A line. One of these panels was selected for study. It was 1/16 inch thick aluminum alloy sheet, 20 inches wide and 48 inches long, rivetted at its edges to inner stiffeners. The permanent inward deformation of this panel relative to its edge supports was 1/2 $\pm$ 1/8 inch. The stiffeners were also permanently deformed inwardly a small amount. However, because of the added analytical complexity required to treat stiffeners, this stiffener deformation was ignored in the present analysis. The small, aluminum alloy building sustained damage to a wall that faced the explosion site. This damage consisted of general permanent inward deformation of amplitude equal to 2 $\pm$ 1/8 inch. The wall was 95 inches high, 96 inches wide, 1/32 inch thick and was normal to A line.

The damage analysis of the trailer and metal building panels is based on a structural analysis of metal plates subjected to blast reported in Reference 2. The damage analysis of the concrete-block wall utility house is based on the well-known value of actual blast peak over pressure required to shatter a concrete-block wall, Reference 3. In both of these analyses, the blast overpressure at a distance from an explosion is related to the amount of blast damage caused by the explosion. Blast pressure decay with distance from the site of an explosion, the information used to tie together observed damage and quantity of explosive, is well known. Such information is given in Reference 4.

As described previously, the process TNT in the A line N and P building was distributed along three walls of the building in a variety of process vessels as well as in storage containers in the remelt room. Also, in its various process stages, the TNT content of the continuous process material varied from essentially 0% to 100% TNT around the three walls of the building. Because of the lack of sufficient information on the treatment of the effects of blast from a continuously distributed explosive source whose purity varies with location, the present study simply treats the observed structural blast damage as caused by the explosion of a specific amount of pure, spherical TNT located at the center of the A line N and P building. The exact influence of these assumptions on the final estimated quantity of TNT that exploded is not known. However, for the purposes of this present study, it probably exerts a relatively minor effect on the exact TNT explosive yield.

B. Analysis of Trailer and Metal Building Side Panel Damage

As stated earlier, the analysis of the trailer and metal building panel deformation damage is based on the method developed in Reference 2.

The approach utilizes a semi-inverse energy method of solution. In its development, the blast-deformation damage process is characterized by the law of conservation of energy. Approximate expressions for the work done on the panel by the blast and the panel strain energy are derived. An assumed deformation pattern is used to obtain the final form of the strain energy. The work done on the panel by the blast is

[2] Donald F. Haskell, "Deformation and Fracture of Tank Bottom Hull Plates Subjected to Mine Blast," Ballistic Research Laboratories Report No. 1587, May 1972. (AD #901628L)

[3] The Effects of Nuclear Weapons, Department of the Army Pamphlet No. 39-3, April 1962, P. 163.

[4] H. J. Goodman, "Compiled Free-Air Blast Data on Bare Spherical Pentolite," Ballistic Research Laboratories Report No. 1092, Feb 1960. (AD #235278)

found by considering the energy flux density of the blast wave normally reflected from the panel. Because of the gross deformation incurred by blast, elastic behavior of the panel material is neglected. The panel is assumed to behave as a rigid-linear strain hardening material. This allows the strain energy to be reduced to a simple expression which, when combined with the energy from the blast in the conservation of energy relation, yields the following explicit equation for transverse deformation, D:

$$D = \left[\frac{104.14 \ Pn^2 \ \Delta t \ ab}{h(F_{TY} + F_{TU}) \ (\beta + \frac{1}{\beta} + .406)} \right]^{1/2} , \text{ in.} \qquad (1)$$

where

- Pn = normally reflected pressure, psi
- Δt = time duration of the positive phase of the blast wave, sec.
- a, b = panel width and length, respectively, in.
- h = panel thickness, in.
- β = b/a
- F_{TY}, F_{TU} = panel material tensile yield strength and ultimate strength, respectively, psi.

This deformation equation makes it possible to calculate the deformation of a panel that would be caused by the blast pressure from an explosion of a certain amount of explosive at a known distance from the panel. If the time for a release wave, T_R, to travel from the panel's edge is less than the time duration of the positive phase, T_R is used in the deformation relation instead of Δt. The release time is given by

$$T_R = \frac{d_{min}}{U_s} , \text{ sec.} \qquad (2)$$

where

- d_{min} = minimum distance from the panel midpoint to the nearest free edge, in.
- U_s = shock velocity in air, in./sec

Normally reflected pressure data is given in Reference 4 for free-air blast of bare spherical pentolite as a function of scaled distance from the explosive. This information may be easily converted to conform to the Radford Army Ammunition Plant situation: surface burst of TNT. Peak pressure for TNT may be obtained from this pentolite information by dividing the pentolite pressures by 1.05. According to Reference 5, peak overpressure in air obtained from pentolite is 1.05 times higher than the peak overpressure from TNT. In addition, the free-air blast pressures of Reference 4 may be converted to the higher pressures generated by a surface burst by employing an effective explosive weight 1.7 times higher than the actual weight. According to Keefer, Reference 6, a surface burst is found to generate peak overpressure at ground level corresponding to an explosive weight equal, on the average, to 1.7 times the actual weight of explosive detonated.

Material property data on the trailer and aluminum panel building were obtained from ALCOA. According to the ALCOA Aluminum Company, Reference 7, typical material supplied by ALCOA for trailer bodies is 5052-H34 aluminum alloy sheet with yield and ultimate strength of 31,000 psi and 41,000 psi, respectively. Typical material supplied for small, metal buildings is 5050-H34 aluminum alloy sheet with yield and ultimate strengths equal to 24,000 psi and 31,000 psi, respectively.

By using these material properties, panel dimensions and their respective distances from the center of the A line N and P building, plots of TNT weight versus deformation amplitude were prepared for the trailer and aluminum panel building. These plots are shown in Figures 2 and 3. In these figures, deformation amplitude as given by Equation 1 is represented by the abscissa and the amount of TNT required to cause this deformation is represented by the ordinate. The observed deformations and their estimated measurement errors, along with the TNT weights to which they correspond, are indicated on the figures. As shown by Figure 2, the measured deformation corresponds to 7600 lbs of TNT bounded by 6200 lbs and 8600 lbs due to the estimated 1/8 inch measurement error. In Figure 3, the measured deformation is shown to correspond to 3200 lbs of TNT with bounds of 5000 lbs and 1600 lbs due to the estimated measurement error. These results differ appreciably. The TNT weight as indicated by the observed deformation of the aluminum panel building is more than double the value indicated by the observed trailer panel deformation. This large difference may have been caused by the relative

[5] Engineering Design Handbook, Explosives Series, Properties of Explosives of Military Interest, AMCP 706-177, March 1967, p. 274.

[6] J.H. Keefer, private communication at the Ballistic Research Laboratories.

[7] ALCOA Aluminum Company, Baltimore, Maryland Office, private communication.

locations of these objects. The aluminum panel building was considerably farther from the explosion site than the trailer. The blast pressure distribution in the vicinity of the A line N and P building must have been considerably altered by the revetted design of the A line N and P building from that obtained from a simple surface burst. The A line N and P building was designed to direct the blast skyward. Consequently, the flow field in the vicinity of the A line N and P building must have been drastically different from the flow field of a surface burst with no obstacles in the path of the flow field. The effects of this near field disturbance would have diminished with distance from the explosion site. Therefore, the flow-field at the aluminum panel building was probably closer to the classical surface burst blast field upon which the present calculations are based than the situation at the trailer. Consequently, more credence is placed on the TNT estimates obtained from the aluminum panel building calculations than on the much lower values from the trailer calculations. As will be shown next, the aluminum panel building TNT estimate is in good agreement with the results of the damage analysis of the concrete-block wall utility house.

C. Analysis of Concrete-Block Utility House Wall Damage

Analysis of the utility house wall damage was based on existing information. According to Reference 3, blast wave peak incident overpressure equal to two psi is sufficient to shatter an eight inch thick unreinforced concrete-block or cinder-block wall panel. This pressure corresponds to the peak incident pressure produced at a point on a rising slope at an elevation of 17 feet and 560 feet horizontal distance from a surface explosion of approximately 8600 lbs of TNT calculated as follows. The explosion occurred at ground level. Consequently, the pressure generated at any point along the ground is larger than the pressure at the same distance away from an explosive charge of equal weight detonated in free air without ground reflection effects. According to Keefer, Reference 6, a surface burst is found to generate peak overpressure on the ground corresponding to an explosive weight equal, on the average, to 1.7 times the actual weight of explosive detonated, i.e.,

$$W_{eq.} = 1.7\ W_{actual}\,.$$

So for an actual weight of 8600 lbs, the equivalent weight is

$$W_{eq.} = 14620\ \text{lbs}.$$

As indicated previously, the utility house was located at a higher elevation than "A" line. Blast pressures increase along a rising slope. The effect of the rising slope from "A" line to the utility house may be estimated by the following empirical equation (Reference 8):

[8] J. H. Keefer and J. D. Day, "Terrain Effects on Blast Wave Parameters," Ballistic Research Laboratories Report No. 1319, April 1966, p. 17. (AD #488080)

$$A = 1 + 2.63 \tan\theta\left(1 - \frac{r_o}{r}\cos 2\theta\right) \qquad (3)$$

where

- A - is the ratio of overpressure on the rising slope to the overpressure at the same distance over flat terrain
- θ - is the slope angle of the topographical shape
- r - is the slant distance from the point of detonation to the start of the slope, inches
- r_o - is a characteristic distance dependent on the cube root of the charge weight = $68.2582\ W^{1/3}$, inches
- W - is the explosive mass, lbs.

For the conditions stated, the amplification factor is 1.0607. The free-field incident overpressure from a detonation of 14,620 lbs equivalent charge at a distance of 560 feet obtained from the free-field data of Reference 3 for 50/50 pentolite is 2.03502 psi. It is amplified to

$$AP_{50/50\ \text{Pentolite}} = 2.1585\ \text{psi}.$$

The pressure may be adjusted to that expected from TNT. According to Reference 5, the peak pressure of 50/50 pentolite is 1.05 times the peak pressure of TNT, or

$$P_{TNT} = 2.06\ \text{psi}.$$

This value is three percent higher than the minimum two psi overpressure required to shatter an unreinforced concrete-block wall. However, it is considered reasonable since part of an adjacent wall of the utility house which did not face the explosion was shattered and the remaining two walls of the building were left intact by the blast. This indicates that the position of the shattered wall which had faced the explosion site was just "on the edge" of the minimum pressure required to shatter the wall. The fact that part of the adjacent wall was shattered indicates that the pressure at the completely shattered wall was probably slightly higher than the minimum required to cause shatter. Therefore, the 8600 lbs TNT estimated to have produced the utility house wall damage is considered reasonable.

D. Summary

In a review of the analysis results for the amount of TNT that exploded at A line, the concrete-block wall utility house damage indicates the TNT weight to be 8600 lbs. This value agrees with the upper value obtained from the aluminum panel building. Calculations based on the permanent deformation of the aluminum panel building wall indicate the amount of TNT that exploded was 7600 lbs with a minimum of 6200 lbs and a maximum of 8600 lbs, corresponding to the lower and upper estimated deformation measurement errors, respectively. The amount of TNT indicated to have detonated by the observed trailer panel permanent deformation is between 1600 and 5000 lbs. Because of the reasons cited earlier concerning the probable flow-field deviation from the classical surface burst situation at the site of the trailer, the flow field at the trailer used in the calculations is not considered representative of the actual conditions. Therefore, the results of the trailer panel damage analysis should be disregarded. This means, then, that since the upper value of 8600 lbs of TNT obtained from the aluminum panel building agrees with the 8600 lbs estimated from the utility house wall damage, this value should be taken as the probable amount of TNT exploded in the A line nitration and purification building. This 8600 lb value may be compared with the best estimate of Reference 9: 8,000 lbs TNT, with an upper limit of approximately 12,000 lbs. These estimates of Reference 9 were the result of an analysis of window breakage at RAAP.

The 8600 lb TNT yield represents about 84 percent of the typical amount of TNT contained in the A line N and P building. It is about 61 percent of the combined amount of both TNT and DNT inprocess explosive material typically found in the building.

IV. USE OF SUPPRESSIVE SHIELDING

A. General

In this section the blast suppression afforded by structures that provide various levels of blast attenuation is presented. In addition, estimates are made of the total cost to repair damage associated with the various levels of attenuation for suppression of the blast effects of three quantities of TNT: 4,000 lbs, 8600 lbs, and 12,000 lbs. The end results are independent of specific structural designs. These results are based on attenuation levels. Definition of the structural design to provide a specific attenuation is not addressed.

B. Blast Field

To provide a framework for the study, an empirical equation generated by dimensional analysis considerations and fitted to data obtained from tests on a variety of suppressive structure designs,

[9] Bruce B. Redpath, "Analysis of Window Damage at Radford Army Ammunition Plant," Memorandum for Director, USAWES Explosive Excavation Research Laboratory, Corps of Engineers, WESEP-74-116, 27 August 1974.

Reference 10, was selected to predict pressure attenuation as a function of vented area-to-total area of the structure, quantity of explosive, distance from the explosive, and size of the suppressive structure. The equation selected for this purpose is

$$P_s = 1186 \left(\frac{R}{X}\right)^{.503} \frac{\alpha_E^{.612}}{Z^{1.93}} \tag{4}$$

where

P_s = side-on overpressure, psi

R = distance from explosive, ft.

Z = $R/W^{1/3}$, $ft/lb^{1/3}$

W = explosive weight, lb

X = characteristic length of panel, ft.

For a square panel, X = length of an edge.

For a rectangular panel,

$$X = (\text{wall area})^{1/2}.$$

α_E = effective vent area ratio

$$\frac{1}{\alpha_E} = \sum_{i=1}^{n} \frac{1}{\alpha_i}$$

$$\alpha_i = \frac{\text{Vented area}_i}{\text{Wall area}}$$

The characteristic length is taken as the average value of the characteristic lengths of the above ground walls of building 9502, or A line. The above ground dimensions of A line are approximately 55 feet wide, 62 feet long, and 11.583 feet high. The average characteristic wall length corresponding to these dimensions is

$$X = 26.02 \text{ feet.}$$

Equation 4 was used to determine the variation in incident pressure with distance from the detonation site of the three quantities of TNT previously stated: 4000, 8600, and 12,000 lbs. Four levels of blast

[10] W. Baker, progress report on suppressive structure pressure attenuation parameter correlation, presented at the Suppressive Structure Technical Steering Committee Meeting, National Space Technology Laboratories, Bay St. Louis, MS, 11-13 Feb 1975.

suppression were considered. Level of suppression is characterized by the ratio of vented area of the suppressive structure to the total surface area, i.e., effective vent area ratio. Vent area ratios considered were .005, .010, .0194, and .0373. Figures 4, 5 and 6 show the variation in side-on pressure with distance calculated by means of the empirical pressure relationship, Equation 4, for 4000, 8600, and 12,000 lbs of TNT, respectively. These figures are constructed for pressure variation over a flat, horizontal ground surface. Also plotted in Figure 5 is the pressure variation constructed on the premise that 8600 lbs of TNT did actually explode at A line. This calculated curve for the estimated amount of TNT that exploded is labeled "original A line design." Also indicated on each of these figures are the blast pressure levels at which the following types of damage have been found to occur, Reference 3: window glass shatter (.5 psi), buckling of corrugated steel and aluminum panel and connection failure (1 psi), and shatter of unreinforced concrete or cinder-block panels, 8-inch thick (2 psi). Within the TNT area, buildings are distributed within the range of 32 to 892 feet from A line. The buildings closest to the center of "A" line are its chemical load and dissolve, metering pump, and utility houses at 32, 36, and 42 ft, respectively. The control laboratory at 202 ft is the next closest significant building. Within the TNT area, the building farthest from the center of "A" line is the guard house at 892 ft. The new Radford administration building, currently under construction, is about 1800 feet from A line. The original A line curve of Figure 4 shows window glass shatter to extend to a range of about 1700 feet, just short of the new administration building. It also shows that damage in the form of buckling of corrugated steel and aluminum panels and connection failure is estimated to extend to 960 feet. This means that, for the type of construction at Radford, exterior walls of pre-engineered metal buildings would be buckled and extensive roof damage would be expected. This did occur at Radford. For example, the office and shop, a pre-engineered metal building at 320 feet from the blast was damaged extensively and the roof of the C line N and P building at 586 feet was damaged, along with the roofs of the office and shop at 930 feet and the guard house at 892 feet. Furthermore, Figure 4 shows that within approximately 550 feet of A line, 8-inch thick, unreinforced, concrete or cinder-block walls should be shattered. This did occur at Radford. For example, heavy damage to unrevetted concrete-block wall buildings did occur out to 560 feet from the center line. As described in detail previously, the concrete-block wall of the C line utility house that faced the explosion at A line was shattered. This wall was 560 feet from the center of A line. This distance approximately marks the outer range of possible shatter of unreinforced concrete or cinder-block panels.

Figure 4 shows that each of the blast pressure-distance curves corresponding to pressure attenuation by controlled venting is lower than the "original A line design" curve. The amount of blast suppression depends on the vent area to total area ratio. Incident pressure decreases with decreasing vent area to total area ratio. This is also demonstrated by Figures 5 and 6 for explosions of 4,000 and 12,000 lbs of TNT respectively.

In Figure 7, the average reduction in pressure from the original A line design pressure caused by an explosion of 8600 lbs TNT as a function of vent area to total area ratio is shown for distances from 200 feet up to 1000 feet from the center of the original "A" line building. This average pressure reduction is seen to decrease with increasing vent area to total area ratio and is almost linear over the vent area to total area range from .01 to .04.

C. Damage Profile

Table 1 is a list of the various structures within the Radford TNT area, their distances from the center of A line N and P building and an estimate of the cost of the damage to each structure incurred by the explosion at A line based on References 11 and 12. The cost associated with each structure listed in Table 1, except A line and its three service buildings, is listed in Appendix A as obtained from Reference 11. In Table 1 damage is listed either as total or partial damage. Total damage as used here means the structure including its contents is a total loss. Damage referred to as partial damage means the windows are shattered with the roof buckled. Roof construction is assumed to consist of corrugated steel or aluminum panels that buckle at 1 psi. For buildings with concrete block walls this partial damage is taken as the sum of IPE equipment, AMC, and one-fifth the total cost as listed in Appendix A. Buildings constructed of corrugated metal walls are assumed to experience total damage if the incident pressure is high enough to buckle the walls and cause connection failure (1 psi). Buildings with unreinforced concrete or cinder block walls subjected to pressure of 2 psi or higher are taken to experience total damage. Table 2 lists the estimated cost of the damage to structures within the TNT manufacturing facility caused by the accident at A line N and P building.

Table 3 lists the various distances from the center of A line within which the incident overpressure is equal to or greater than 0.5, 1 and 2 psi. As discussed previously, 0.5 psi is the minimum incident overpressure at which windows shatter, 1 psi is the minimum pressure at which corrugated steel or aluminum panels buckle and connections fail, and 2 psi is the onset of shattering of unreinforced, 8 inch thick, concrete or cinder block wall panels according to Reference 3. A distance listed in Table 2 corresponding to 1 psi (for example) means that all structures located within that distance constructed of corrugated steel or aluminum panels will suffer buckling damage and connection failure, as well as window glass breakage. For simplicity, the distances listed

[11] PA, A P-15 for Project 5765901 Titled Restore TNT Manufacturing Facility, Lines B and C.

[12] Report of Proceedings for Board of Investigation, Explosion in TNT Area, Radford AAP, Radford, Virginia, 31 May 1974.

in Table 3 are based on the blast pressure above a flat, horizontal ground surface. These distances have been obtained from Figures 4, 5, and 6 for the four vent area to total area ratios treated (0.005, 0.01, 0.0194 and 0.0373) as well as for the calculated pressure distribution caused by detonation of 8600 lbs of TNT in the original A line-design building. It may be seen that the incident overpressure from the 8600 lbs of TNT estimated to have exploded at A line is calculated to be higher than 2 psi out to a distance of 550 feet from A line if the ground had been flat and horizontal. This distance, when entered into Table 1, indicates that approximately 30 structures were subject to incident overpressure higher than 2 psi. By entering into Table 1 the 960 feet from Table 3 corresponding to 1 psi from the original A line design, it may also be seen that a total of about 41 structures lay within the 1 psi (corrugated metal panel buckling and connection failure damage) pressure regime. All structures within the TNT area and beyond, up to 1700 feet from A line, were subject to window glass breakage pressure.

The maximum damage distance information in Table 3 for explosion of 8600 lbs of TNT at A line is shown graphically in Figures 8 through 12 for the approximate situation at the time of the Radford accident (labeled here as the "original" design) and the predicted conditions to be found if suppressive structures of the various levels of attenuation, characterized by the vent area ratio, had been in place at the time of the accident.

In the TNT area layout equal pressure contours are drawn at the distance from the center of A line building that correspond to incident overpressures of 2, 1, and 0.5 psi. These equal pressure contours are circular because, as described previously, the ground has been assumed to be flat and horizontal for the sake of simplicity. In the figures the outline of the TNT area, physically marked on the ground by a fence, is indicated by a light dashed irregular line. A, B, and C line nitration and purification buildings are labeled as such. Only the more prominent structures are shown in these figures. Totally damaged structures, those with buckled corrugated metal walls, and buildings with roof and window damage are blackened within their outlines. The inner, heavy continuous circle is the 2 psi equi-pressure contour within which unreinforced concrete or cinder-block walls are shattered. The heavy, long dashed circle is the 1 psi contour - this contour marks the extent of the pressure region that can cause buckling of corrugated steel or aluminum panels and connection failure. The outer, heavy, short-dashed circle marks the boundary of window glass shatter.

As may be seen in going from Figure 9 to Figure 12, the equal pressure circles become progressively smaller in diameter as the vent area ratio is reduced from .0373 to .005. This is reflected in the effect of suppressive structures as a potential decrease in the amount of damage done to the TNT plant. A total of 41 structures in the TNT plant received significant structural damage from the 31 May 1974 accident.

This may be compared with the reduced number of structures estimated to sustain the same type of damage if the A line nitration and purification building had been of the suppressive structure type. It is estimated that a total of 34, 27, 21 and 13 structures would have sustained significant structural damage from an explosion of 8600 lbs of TNT within a suppressive structure with vent area ratios equal to 0.0373, 0.0194, 0.010 and 0.005, respectively. This represents a range of potential reduction in the number of structures with major structural damage from 17 to 68%. The potential reduction in major structural damage to buildings would be higher if all three N and P buildings had been of the suppressive structure type. In this case, it is estimated that the total number of structures that would sustain major structural damage from an explosion of 8600 lbs of TNT within a suppressive structure with vent area ratios equal to 0.0373, 0.0194, 0.010 and 0.005 would decrease to 32, 25, 19, and 11 respectively. This represents a range of potential reduction in buildings with major structural damage from 22 to 73%. However, the number of damaged buildings does not convey as clear a picture of the potential damage reduction as does the cost of the damage

D. Damage Cost Estimates

Table 4 lists cost estimates of the damage incurred by the 31 May 1974 Radford accident along with cost estimates of predicted damage from accidents within N and P buildings constructed of the suppressive structure type. Three quantities of TNT are considered: 4000 lbs, 8600 lbs and 12000 lbs. Four levels of suppression are considered with vent area ratios of 0.005, 0.010, 0.0194 and 0.0373. In addition, estimates are made for the case in which a suppressive structure is utilized only at A line, the site of the explosion, as well as for the case in which all three nitration and purification lines are of the suppressive structure type.

The $7,484,000 figure labeled as the baseline cost estimate for damage incurred by the Radford accident includes $6,008,131 attributable to damage to the 41 structures within the TNT area listed in Table 1, $1,286,000 in physical damage and $190,000 in private property damage outside the TNT area but within the remainder of the Radford Army Ammunition Plant, Reference 12. The $6,008,131 figure for the 41 structures within the TNT area is equal to the total estimate of $5,333,450 for FY75 as listed in Table 2 multiplied by 1.1265, an average factor for escalation from FY75 to FY76 employed in Appendix A. The final baseline cost estimate of $7,484,000 does not include the cost of the A line nitration and purification building itself. It also does not include the estimated costs of miscellaneous equipment and small structures within the TNT area ($856,365), automobile damage ($100,000), off-plant property ($28,000), off-plant injury ($25,000) and vehicle and MHE ($93,000). These estimates total $1,102,365 in FY76 projections. The cost of this damage is not included in the

$7,484,000 baseline cost because of the desire in this study to include only those items with relatively firm cost estimates and those items that could be readily located on the available drawings and treated by the damage analysis techniques employed here.

The information in Table 3 is plotted in Figures 13 through 21. In Figures 13-15 the effect of blast suppression level on estimated co : of the resulting damage is shown for the cases of suppressive structure at A line only and suppressive structure at all three N and P lines. Also shown on each figure for comparison purposes is the $7,484,000 Radford baseline damage cost estimate. As indicated on each figure, damage costs decrease as the vent area to total area ratio decreases i.e., as the level of blast suppression increases. It may also be seen from these figures that damage costs are from one to two million dollars less if a suppressive structure is employed at all three N and P lines rather than at A line only (except for a 4000 lb TNT explosion within a suppression, vent area ratio from 0.005 to about 0.0175). It should also be noted that the highest damage costs with a suppressive structure at A line only for accidents of 4000, 8600 and 12000 lbs TNT are 4, 2.3, and 1.5 million dollars less than the Radford baseline damage cost.

In Figures 16 through 19 the information in Table 3 is plotted to illustrate the effect of explosive quantity on damage costs. For purposes of comparison the damage cost variations for the case of suppressive structure at A line only are shown along with the cost variations for the case of suppressive structure at all three N and P lines. In general, these figures show a rise in damage cost as the quantity of explosive increases until some quantity is reached beyond which the cost remains relatively constant. This quantity of TNT (or rather range in TNT) at which damage cost begins to "level out" apparently depends upon the vent area ratio. In Figure 20 damage cost for the case of suppressive structure at A line only is plotted versus quantity of TNT for the various vent area ratios considered. Figure 21 is a similar plot for the case in which the suppressive structure type of construction is employed at all three N and P lines.

The ratio of the estimated cost damage from an explosion of 8600 lbs TNT that would be incurred at the Radford Army Ammunition Plant if N and P buildings of the suppressive structure type were employed to the estimated baseline cost of damage, $7,484,000, caused by the 31 May 1974 accident at the A line building, not of the suppressive structure type, in which it is estimated that 8600 lbs of TNT exploded, is listed in Table 5 and plotted in Figure 22 as a function of level of blast suppression. As described previously, the $7,484,000 baseline figure does not include the cost of the destroyed A line building nor other miscellaneous items. The total estimated damage cost of these miscellaneous items is $1,102, 365. A firm cost estimate of the A line building itself was not available to this study. It is seen in Figure 22 that the damage cost with suppressive structure in place -to - Radford baseline damage cost ratio increases with an increase in vent area ratio i.e., as the level of blast suppression decreases. For a suppressive structure at A line only the damage cost ratio increases from .32 to .70 over a range in vent area ratio from 0.005 to 0.0373. This variation is almost linear. If suppressive structures are employed at all three lines the damage ratio is about half the damage ratio for a suppressive structure at A line only over the range of vent area ratio considered. With a suppressive structure type building employed at all three N and P lines, it is estimated that the cost of the damage caused to the Radford Army Ammunition Plant by an accident of 8600 lbs of TNT within the A line could be controlled to range from 16% to a maximum of 38% over the range of suppressive levels considered in this study. Obviously, as shown by the dashed line in Figure 22, if the level of blast suppression is increased to the point that no blast at all escapes the structure (vent area to total area equal to zero), the damage cost ratio becomes zero. At this point the damage would be completely confined to the structure and its contents.

The reduction in the cost of damage estimates listed in Table 4 for the estimated TNT yield at the RAAP incident is shown plotted in Figure 23 as a function of vent area to total area ratio. As may be seen from this figure, considerable destruction could have been avoided if the N and P buildings had been constructed of the suppressive structure type. Destruction ranging from 30% to at least 68% could have been avoided if a suppressive structure had been employed at A line only. It is estimated that even greater damage could have been avoided if all three N and P buildings had been of the suppressive structure type. This savings ranges from 62% to at least 84% for the levels of blast suppression considered in this study. As indicated by Figure 23, further savings could have been made possible with higher levels of blast suppression, that is, with vent area to total area ratio less than 0.005.

V. CONCLUSIONS

1. The explosive yield in the 31 May 1974 Radford AAP accident is estimated to be equivalent to 8600 lbs TNT.

2. Based on this yield, if the A line N and P building had been of the suppressive structure type, from 30% to at least 68% of the destruction, exclusive of damage to the N and P building itself, could have been avoided. If all three of the N and P buildings had been of the suppressive structure type, from 62% to at least 84% of the destruction could have been avoided.

3. Even more destruction could have been avoided than estimated above if suppressive structure with higher levels of blast suppression than considered in this study had been employed at RAAP.

4. Damage costs for accidental explosions of 4000 lbs and 12000 lbs TNT, as well as 8600 lbs TNT, have been estimated and included herein. These figures show that, as to be expected, damage decreases as the level of blast suppression is increased.

APPENDIX A

ESTIMATES OF DAMAGE COSTS OF INDIVIDUAL ITEMS WITHIN TNT AREA (REF 11)

INCLOSURE NO. 1

SCOPE OF WORK

Bldg. No.	Title	CofE	IPE Equip.	AMC	Total Cost
9500	Nitration House	$ -	$ 28,600	$ 961,730	$ 990,330
A9500	Utility House	88,750	2,300	2,000	93,050
B9500	Metering Pump House	72,950	12,900	6,000	91,850
C9500	Chemical Load and Dissolve House	41,900	10,400	4,000	56,300
9501	Nitration House	-	29,240	1,047,690	1,076,930
A9501	Utility House	88,750	2,300	2,000	93,050
B9501	Metering Pump House	72,950	12,900	6,000	91,850
C9501	Chemical Load and Dissolve House	41,900	10,400	4,000	56,300
9503	Finishing House	65,240	15,000	140,010	220,250
A9503	Catch Tank House	54,700	-	-	54,700
9504	Finishing House	65,240	11,500	174,710	251,450
A9504	Catch Tank House	54,200	-	500	54,700
9506	Loading Dock	40,800	-	500	41,300
9507	Control Laboratory	-	13,000	-	13,000
9508	Office and Shop	265,400	-	3,000	268,400
9509	Gate House	1,200	-	-	1,200
9510	Spent Acid Recovery	64,700	-	700	65,400
9511	Chemical Storage House	247,000	-	-	247,000
9512	Field Toilet	14,200	-	-	14,200
9513	Field Toilet	14,200	-	-	14,200
9516	Oleum Unloading Station	-	-	900	900
9517	Search House	5,800	-	-	5,800
9522	Toluene Unloading Station	-	-	900	900

INCLOSURE NO. 1 (Continued)

Bldg. No.	Title	CofE	IPE Equip.	AMC	Total Cost
9523	Toluene Storage	$ 500,000	$ -	$ 1,200	$ 501,200
9524	60 PC NA Storage	-	-	1,900	1,900
6525	98 PC NA Storage	-	-	1,900	1,900
9526	Oleum Storage	-	-	1,900	1,900
B9529	Red Liquor Control House	45,500	19,000	-	64,500
C9529	Settling Area	-	-	481,250	481,250
D9529	Destruction Area	80,600	9,000	1,500	91,100
9543-1	Conveyor From Building 9503	47,050	-	750	47,800
9543-2	Conveyor Fron Building 9504	47,050	-	750	47,800
9544	Paint-Oil Storage	10,700	-	100	10,800
9545	Spent Acid Surge Tanks	13,250	-	150	13,400
9546-1	Lime Mix House	32,100	-	-	32,100
9551	Tank Car Neut. Dock	3,300	-	-	3,300
T-112	Temporary Building	-	-	5,600	5,600
905	Process Yard Piping	271,200	-	3,300	274,500
—	Underground Utilities	31,550	-	350	31,900
—	Aboveground Utilities	154,950	-	1,550	156,500
904	Telephone Lines	-	-	19,300	19,300
—	Fire Alarm System	-	-	15,100	15,100
—	P. A. System	-	-	500	500
910	Road Repair (minor)	13,000	-	-	13,000
901	Outside Electric Lines	104,200	-	1,100	105,300
	PROJECT TOTAL FY-75	$2,654,330	$176,540	$2,892,840	$5,723,710
	Escallation From FY-75	325,396	21,185	377,597	724,178
	PROJECT TOTAL FY-76	$2,979,726	$197,725	$3,270,437	$6,447,888

Misc Costs	687,000
Equipment from FY-75	1,596,000
Total B + C Lines	$8.7 M

APPENDIX B

MISCELLANEOUS DAMAGE COST ESTIMATES (REF 12)

Automobile	$100,000
Off-Plant Property	28,000
Off-Plant Injury	25,000

Building 9502	1,550,314
Plant Damage Outside of TNT Area	1,286,000
Vehicle and MHE	93,000
Private Property	190,000

Table 1. Building Construction, Damaging Pressures, and Cost of Damage Estimates

RPT BLDG NO	DISTANCE FROM CENTER OF A LINE FT	BLDG NO ACTUAL	DESCRIPTION	TYPE OF CONSTRUCTION		DAMAGING PRESSURE			COST OF DAMAGE, $	
				WALLS	ROOF	WALLS PSI	ROOF PSI	WINDOWS PSI	TOTAL	PARTIAL
1	32	C9502	Chemical load & dissolve house	B	CR	2	1	.5	56,300	22,780
2	36	B9502	Metering pump house	B	CR	2	1	.5	91,850	33,490
3	42	A9502	Utility house	B	CR	2	1	.5	93,050	21,110
4	148	9514	Field toilet	CR	CR	1	1		14,200	14,200
5	148	9513	Field toilet	CR	CR	1	1		14,200	14,200
6	202	9507	Control lab	CR	CR	1	1	.5	268,400	268,400
7	204	B9505	Finishing house loading dock hse	CR	CR	1	1	.5	45,800	45,800
8	212	C9529	Settling area (10 tanks)	CR	CR	1	1	X	65,400	65,400
9	226	B9501	Metering pump house	B	CR	2	1	.5	91,850	33,490
10	246	A9501	Utility house	B	CR	2	1	.5	93,050	22,050
11	254	9504	Finishing hse (revetted)	REVETTED	CR	X	1	.5	251,450	251,450
12	262	D9529	Destruct area	TANKS		X	X	X	91,100	91,100
13	274	9501	N&P bldg	REVETTED	CR	X	1	.5		1,076,930
14	282	A9505	Catch tank house	B	CR	2	1	.5	54,700	11,340
15	296	B9504	Finishing house loading dock house	CR	CR	1	1	.5	73,235	73,235
16	302	9545	Spent acid surge tanks	TANKS		A	A	A	13,400	13,400
17	320	9528	Office & shop	CR	CR	1	1	.5	268,400	268,400
18	322	B9529	Destruct area control house	CR	CR	1	1	.5	64,500	28,100
19	346	A9504	Catch tank house	B	CR	2	1	.5	54,700	11,440
20	350	C9501	Chemical load & dissolve house	B	CR	2	1	.5	56,300	25,660
21	352	A9529	Destruct area satellite house	CR	CR	1	1	X	64,500	64,500
22	424	9510	Spent acid recovery	CR	CR	1	1	X	64,400	65,400
23	432	9511	Chemical storage house	CR	CR	1	1	.5	247,000	247,000
24	448	A9503	Catch tank house	B	CR	2	1	.5	54,700	10,940
25	454	9512	Field toilet	CR	CR	1	1	X	14,200	14,200
26	466	A9510	Tank	TANK		X	X	X	X	X
27	476	9503	Finishing house	REVETTED	CR	X	1	.5	220,250	220,250
28	538	B9500	Metering pump house	B	CR	2	1	.5	91,850	33,490
29	542	B9503	Finishing house loading dock house	CR	CR	1	1	.5	73,235	73,235
30	550	9506	Loading dock hse	REVETTED		X	X	X		
31	560	A9500	Utility house	B	CR	2	1	.5	93,050	22,910
32	586	9500	N&P building	REVETTED	CR	X	1	.5		990,330
33	612	9527	Filtered water tank	TANK		X	X	X	X	X
34	632	9521	Loading dock house	CR	CR	1	1	.5	41,300	41,300
35	662	C9500	Chemical load & dissolve house	B	CR	2	1	.5	56,300	22,780
36	676	9544	Paint-oil storage	B	CR	2	1	.5	10,800	10,800
37	730	9508	Office & shop	B	CR	2	1	.5	268,400	56,680
38	748	9523	Toluene storage tank	TANK		*B	*B	X	501,200	501,200
39	868	9519		B	CR	2	1	.5	29,000	5,800
40	868	9517	Search house	B	CR	2	1	.5	29,000	5,800
41	892	9509	Guard house	CR	CR	1	1	.5	6,000	1,200

NOTE: CR - corrugated metal panel
B - concrete block
See notes in Table 2

TABLE 2. Estimated Damage and Cost for Accident

At "A Line" M&P Building No. 9502

PRESS., PSI DIST., FT	REPORT BLDG NUMBER ≥ 2 558	 ≥ 1 978	 $\geq .5$ 1718	DAMAGE TYPE	COST TOTAL DAMAGE $	COST PARTIAL DAMAGE $
	1			T	56,300	
	2				91,850	
	3				93,050	
	4				14,200	
	5				14,200	
	6				268,400	
	7				45,800	
	8				65,400	
	9				91,850	
	10				93,050	
	11			RW		251,450
	12			*		91,000
	13			RW		1,076,930
	14			T	54,700	
	15			T	73,235	
	16			*A		13,400
	17			T	268,400	
	18				64,500	
	19				54,700	
	20				56,300	
	21				64,500	
	22				65,400	
	23				24,700	
	24				54,700	
	25				14,200	
	26				X	
	27			RW		220,250
	28			T	91,850	
	29			T	73,235	
	30			X		
		31		RW		22,910
		32		RW		990,330
		33		X		
		34		T		41,300
		35		RW		22,780
		36		RW		10,800
		37		RW		56,680
		38		*B		501,200
		39		RW		5,800
		40		RW		5,800
		41		T	6,000	

NOTE: T - total damage
RW - roof and window damage
X - damage not expected at these pressures
*, *A - miscellaneous damage
*B - damage from fragments possible

TABLE 3. Damage-Distance from Center of Bldg 9502, "A Line" - Objects Within the Indicated Distances are Damaged

TNT LBS.	INCIDENT PRESSURE PSI	DISTANCE FROM CENTER OF A LINE, FT VENT AREA/TOTAL AREA				
		ORIGINAL DESIGN	.005	.010	.0194	.0373
4000	.5		322	432	560	742
	1.0		200	265	348	460
	2		124	164	217	285
8600	.5	1700	450	600	800	1070
	1	960	278	374	498	660
	2	550	162	230	307	407
12000	.5		524	700	934	1260
	1		320	430	573	764
	2		197	265	354	468

TABLE 4. Damage Costs

		COST, $1000		COST OF DAMAGE SAVED BY SS, $1000	
LBS. TNT	VENT AREA / TOTAL AREA	SS AT A LINE ONLY	SS AT ALL 3 N&P LINES	SS AT A LINE ONLY	SS AT ALL 3 LINES
4000	.005	304	304		
	.010	1180	1180		
	.0194	2891	1678		
	.0373	3568	2354		
8600	.005	2393	1180	5091	6304
	.010	3059	1845	4425	5639
	.0194	3816	2603	3668	4881
	.0373	5207	2878	2277	4606
12000	.005	2806	1592		
	.010	3212	1999		
	.0194	4045	2832		
	.0373	5923	3594		

Baseline Damage Cost Estimate of RAAP accident = $7,484,000

TABLE 5. Ratio of Damage Cost

With suppressive structure in place-to-baseline damage cost at Radford due to explosion of 8600 lbs TNT in building of conventional design (baseline damage cost = $7,484,000).

VENT AREA / TOTAL AREA	SUPPRESSIVE STRUCTURE UTILIZED AT	
	A LINE ONLY	ALL 3 N&P LINES
0.005	.32	.16
0.010	.41	.25
0.0194	.51	.35
0.0373	.70	.38

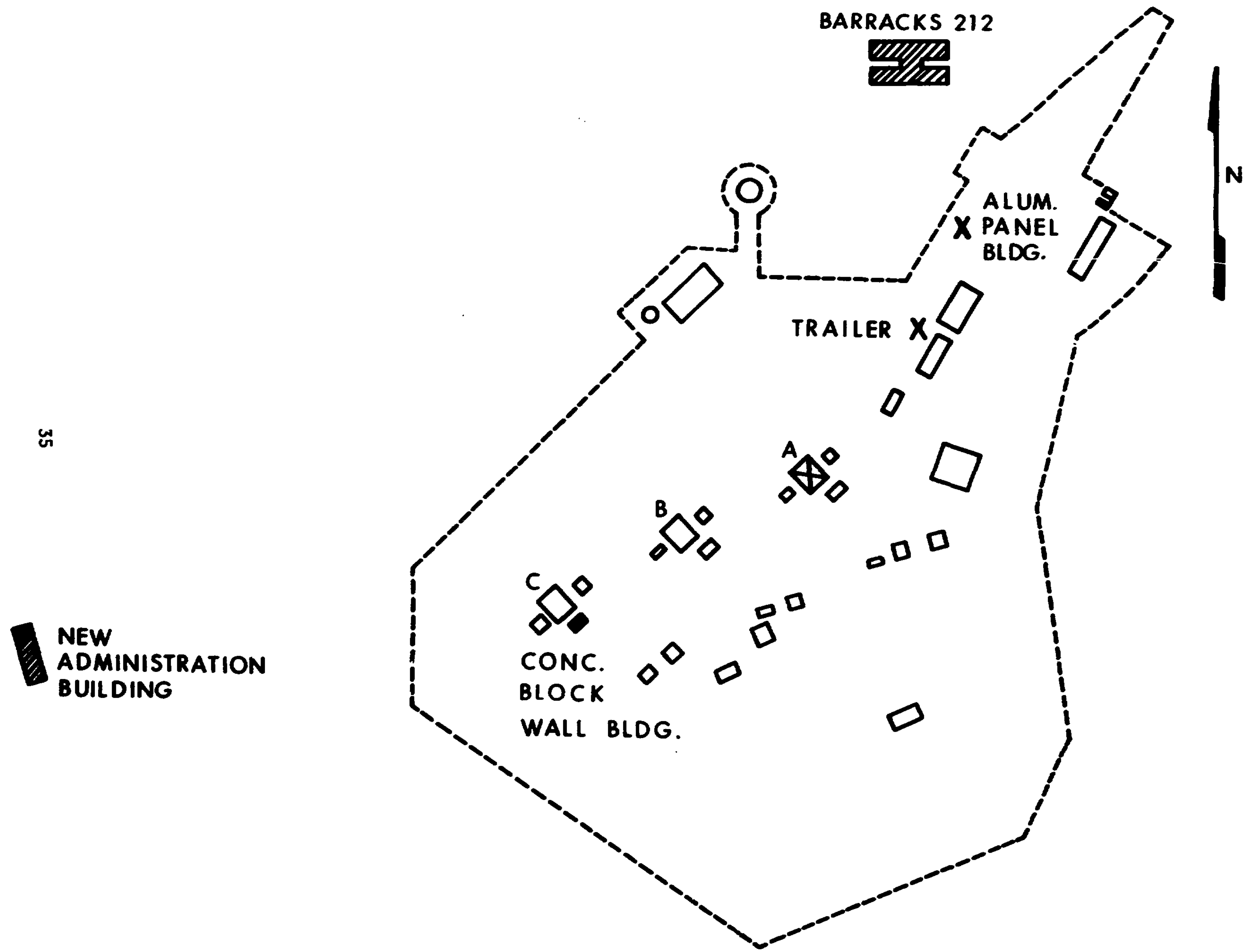

Figure 1. TNT Area Layout

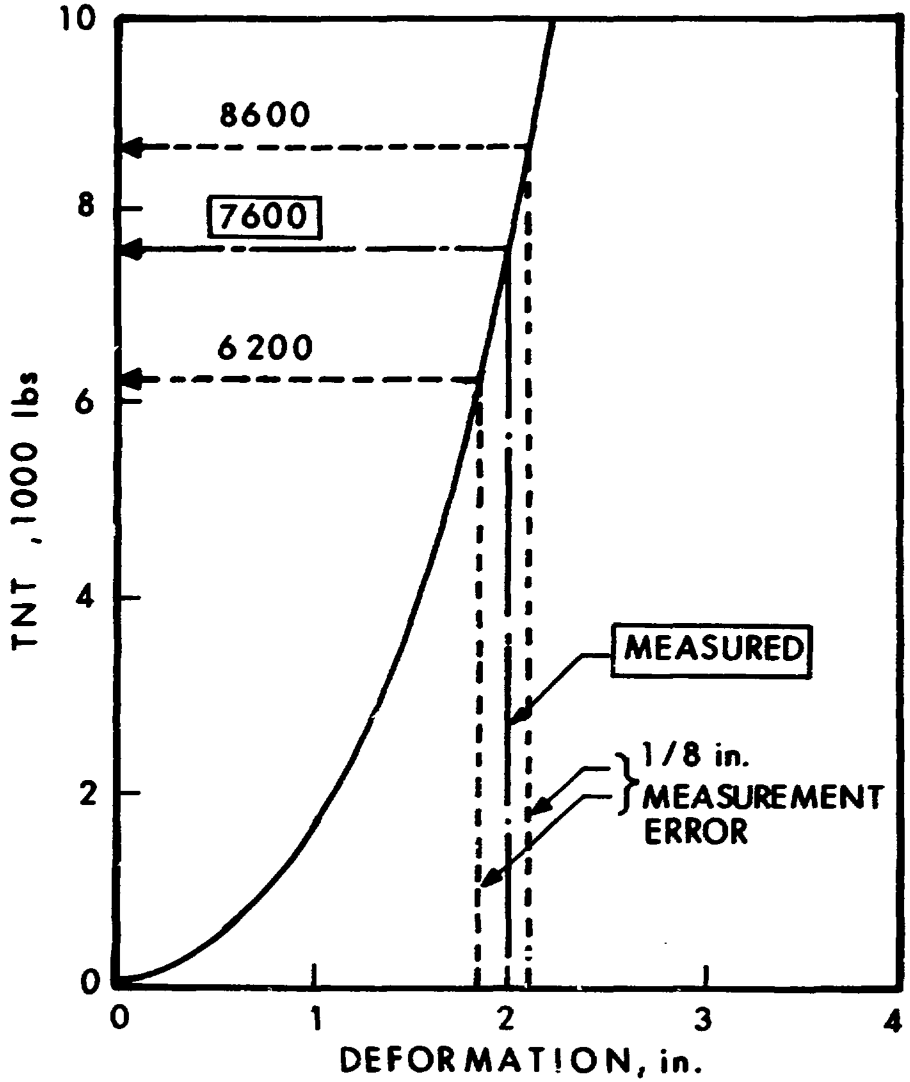

Figure 2. Deformation of Aluminum Panel Building 840 ft. from "A" Line

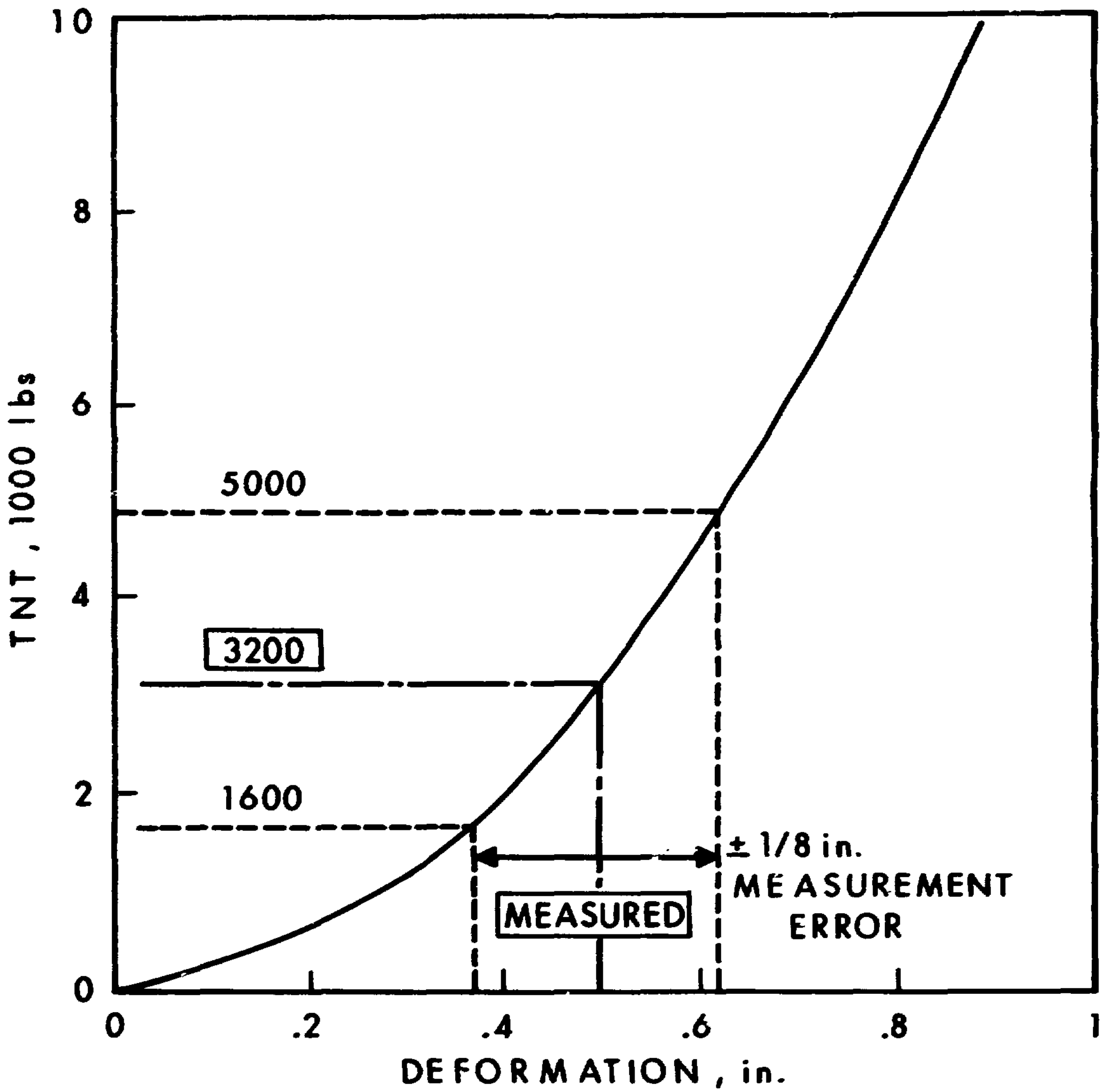

Figure 3. Deformation of Trailer Panel
438 ft. from "A" Line

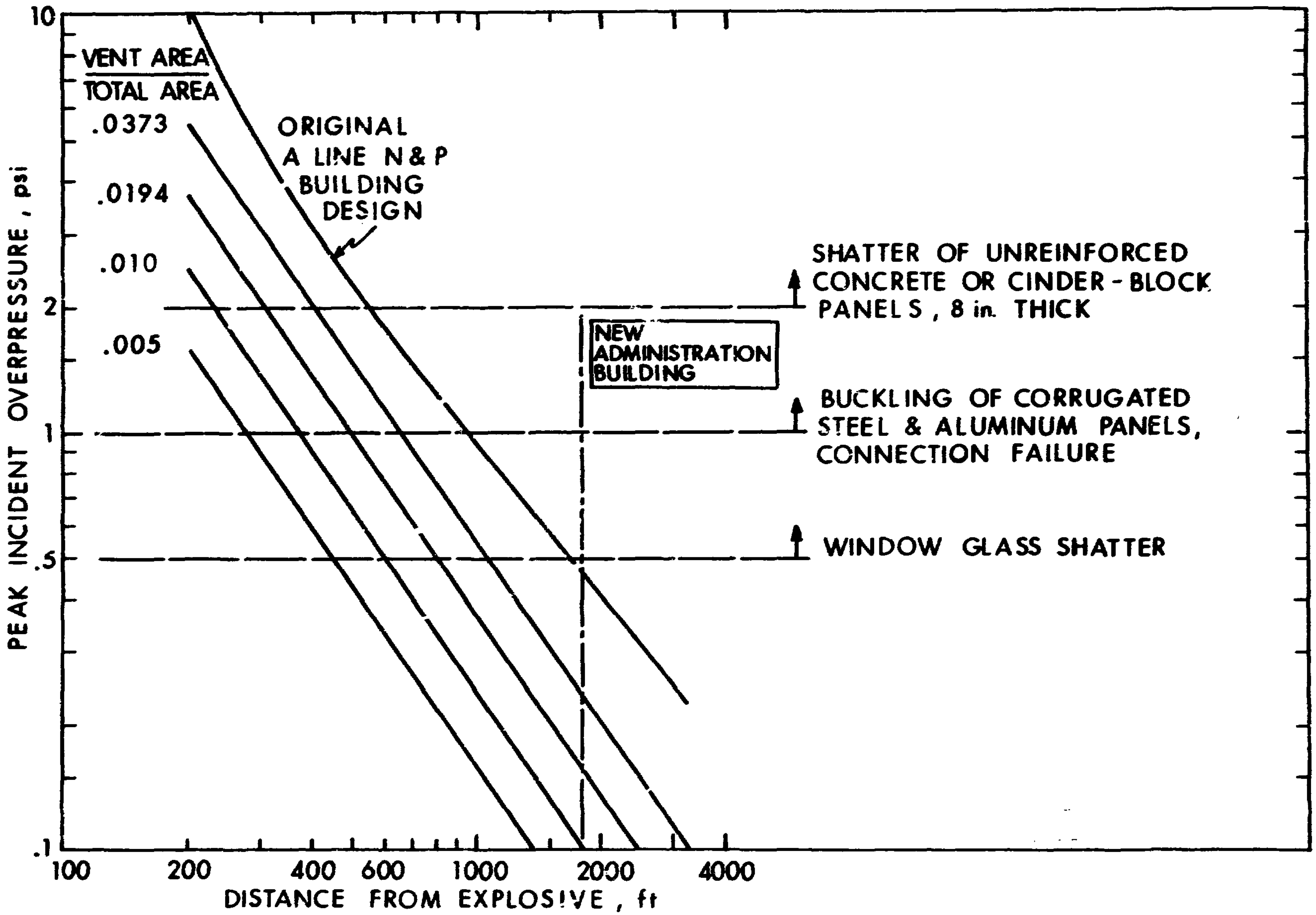

Figure 4. Pressure vs. Distance from Explosive for 8600 lb. TNT Detonation within Building of Characteristic Dimension = 26 ft.

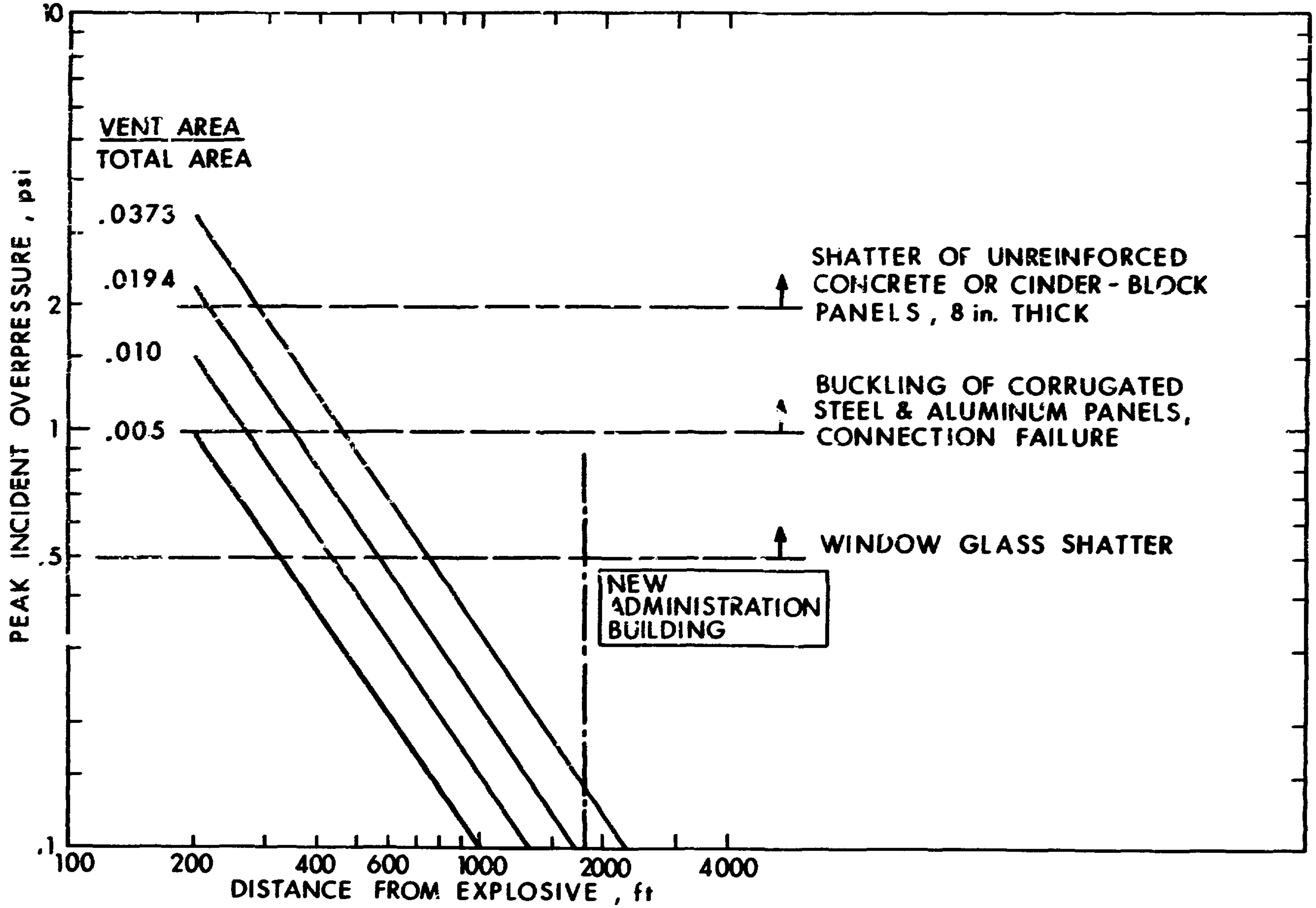

Figure 5. Pressure vs. Distance from Explosive for 4000 lb. TNT Detonation and Characteristic Building Dimension = 26 ft.

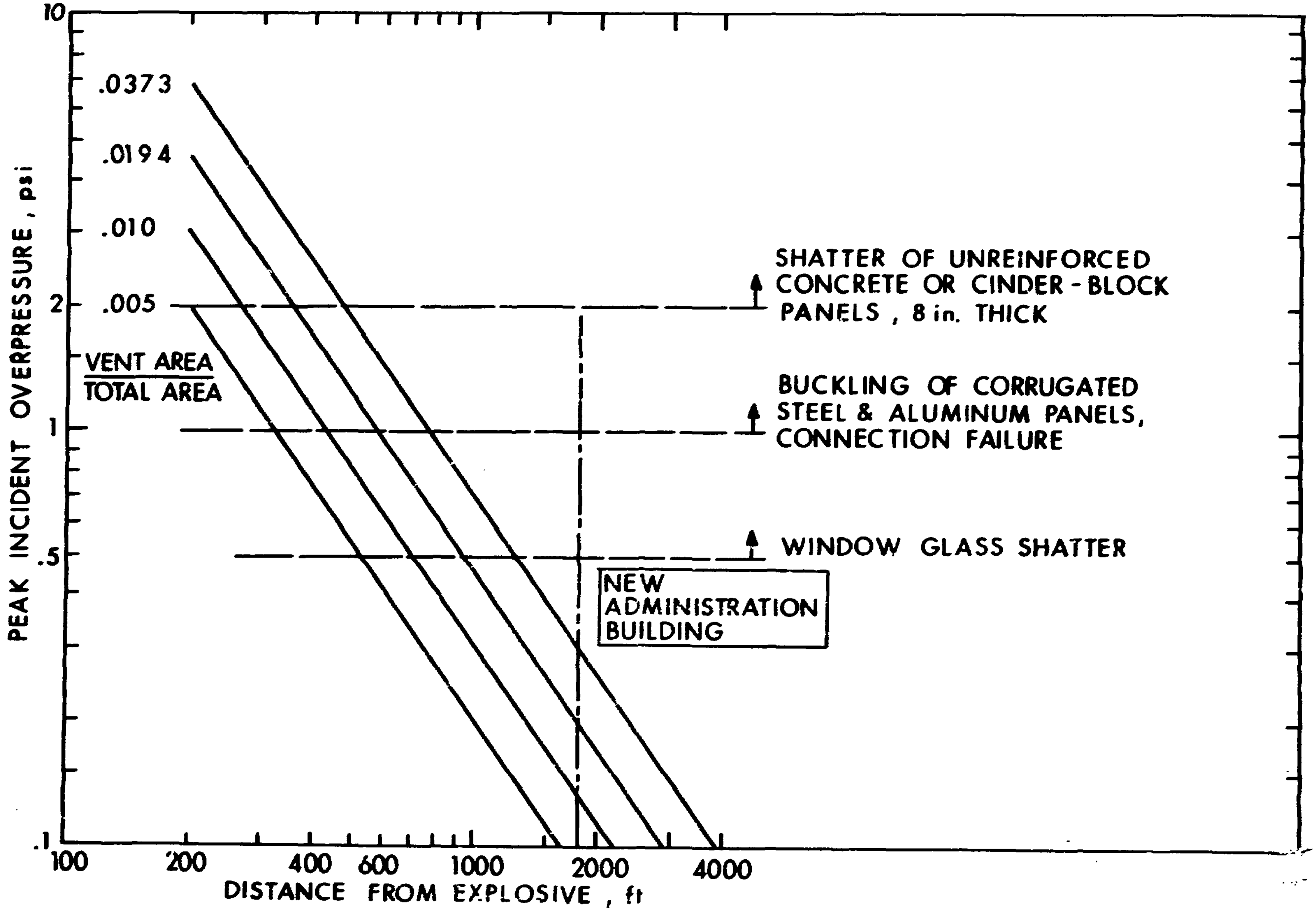

Figure 6. Pressure vs. Distance from Explosive for 12,000 lb. TNT Detonation and Characteristic Building Dimension = 26 ft.

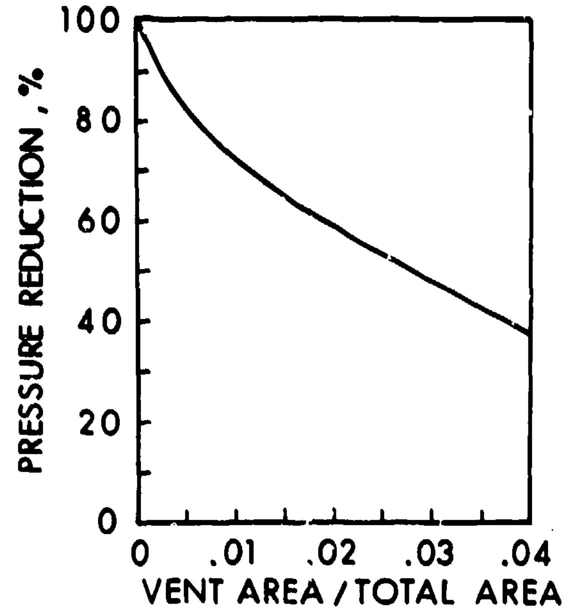

Figure 7. Average Reduction in the Pressure Caused by an Explosion of 8600 lb. TNT within the Original A Line N&P Building for Distances from 200 ft. up to 1000 ft. from the Center of the A Line N&P Building as a Function of Effective Vent Area Ratio

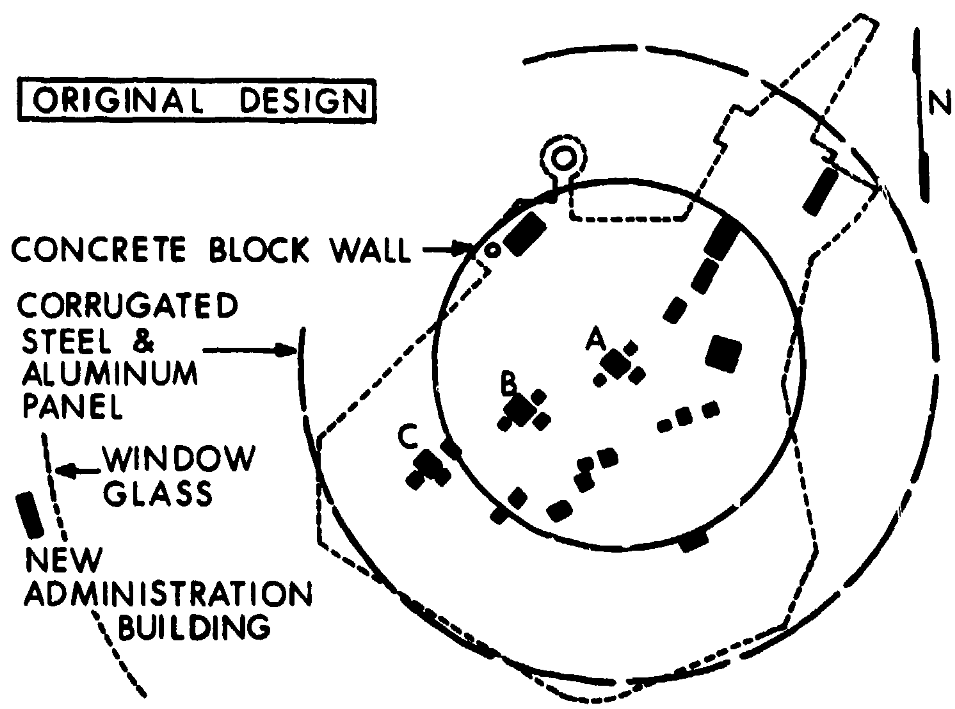

Figure 8. TNT Area Layout

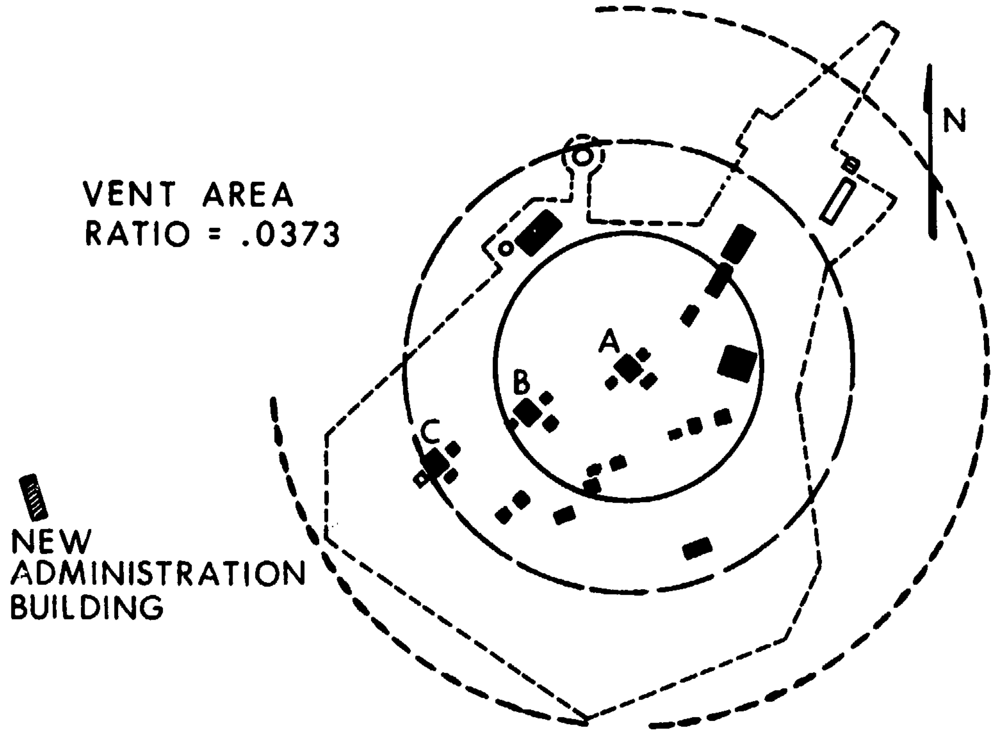

Figure 9. TNT Area Layout

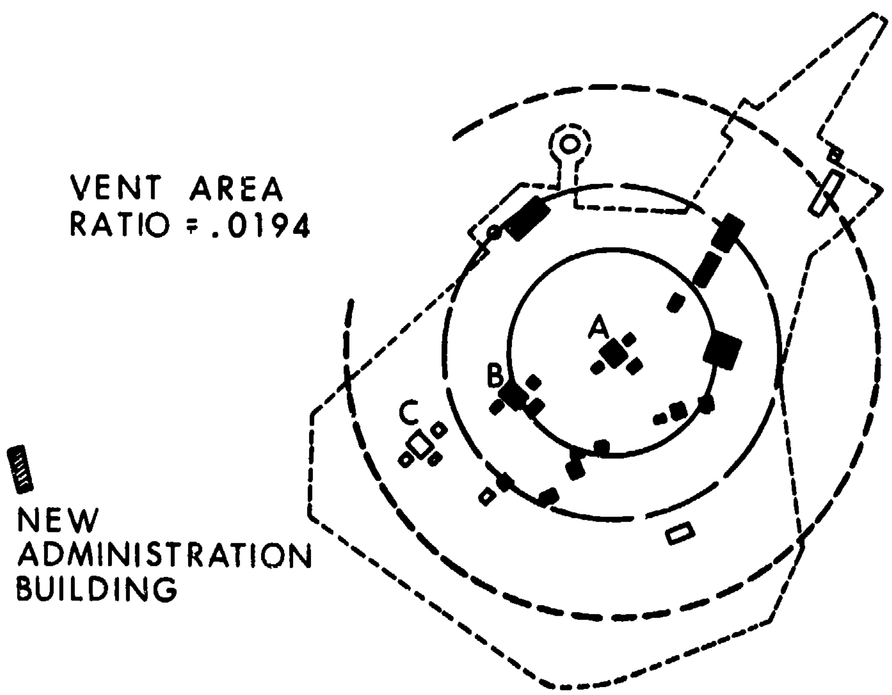

Figure 10. TNT Area Layout

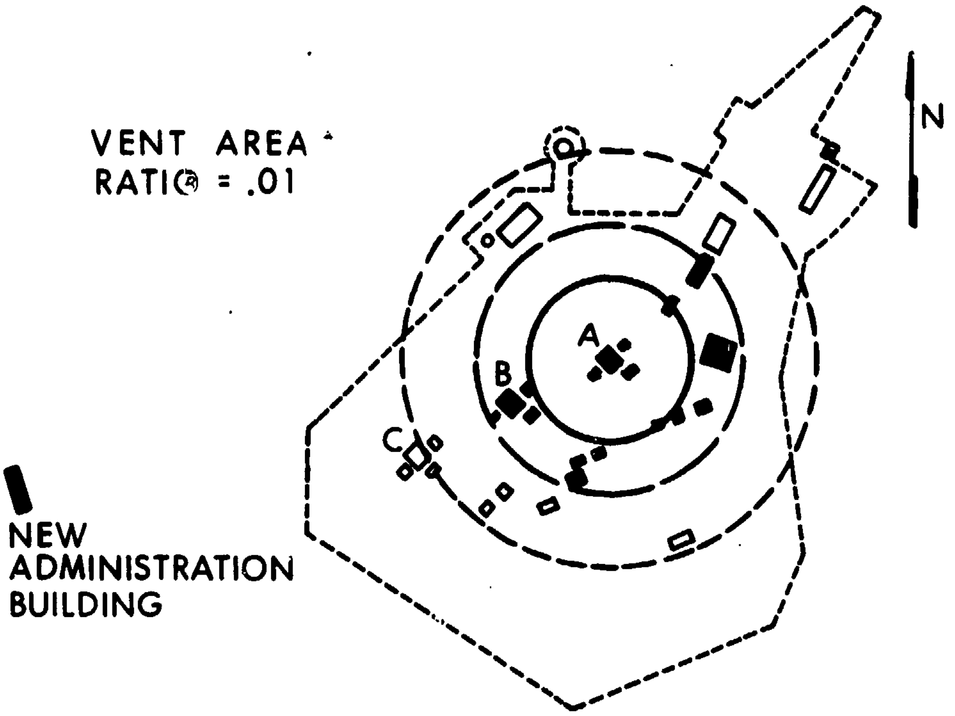

Figure 11. TNT Area Layout

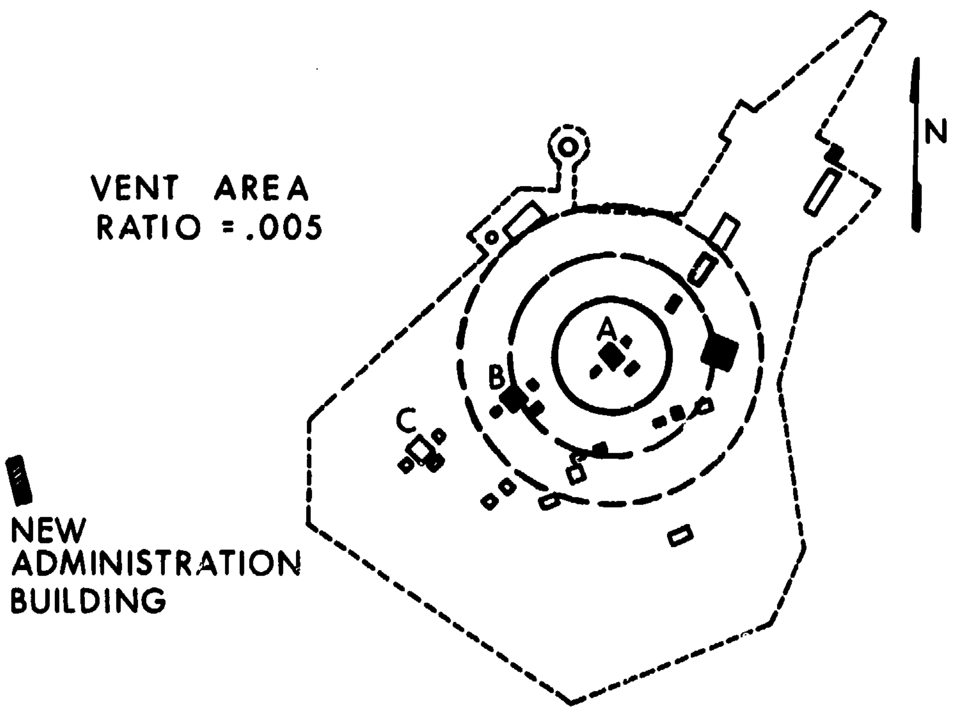

Figure 12. TNT Area Layout

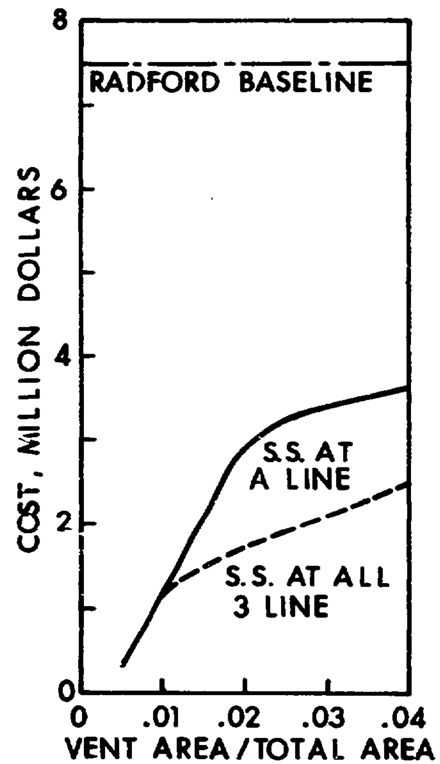

Figure 13. Damage Cost Estimates for 4000 lb. TNT Accident

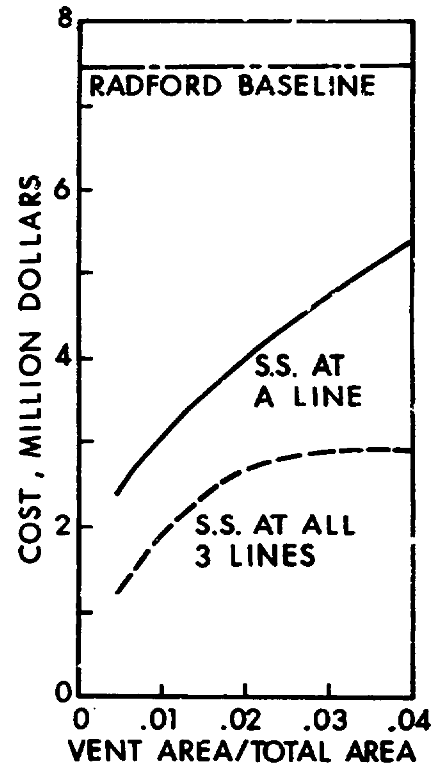

Figure 14. Damage Cost Estimates for 8600 lb. TNT Accident

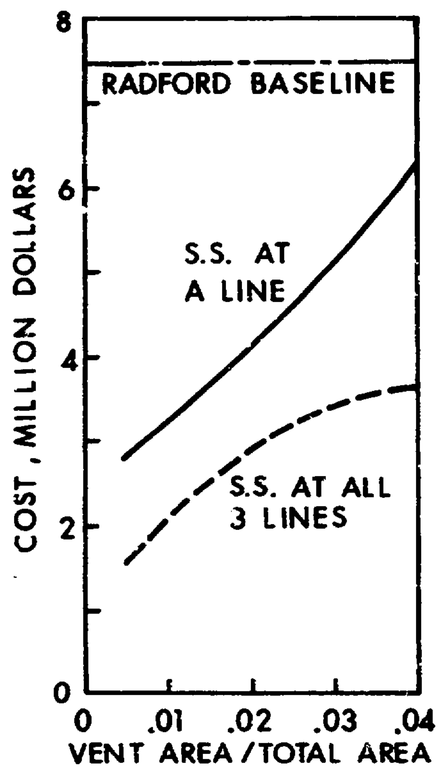

Figure 15. Damage Cost Estimates for 12,000 lb. TNT Accident

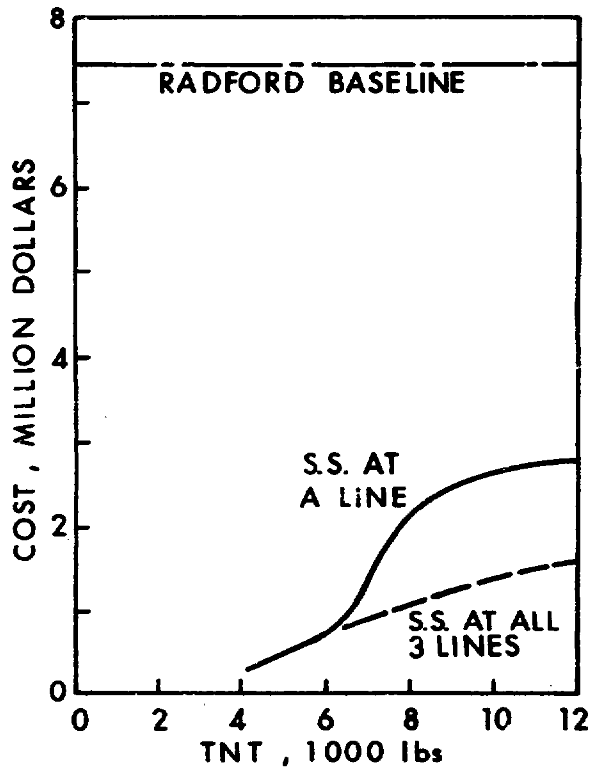

Figure 16. Damage Cost Estimates for Suppressive Structure with Effective Vent Area Ratio = 0.005

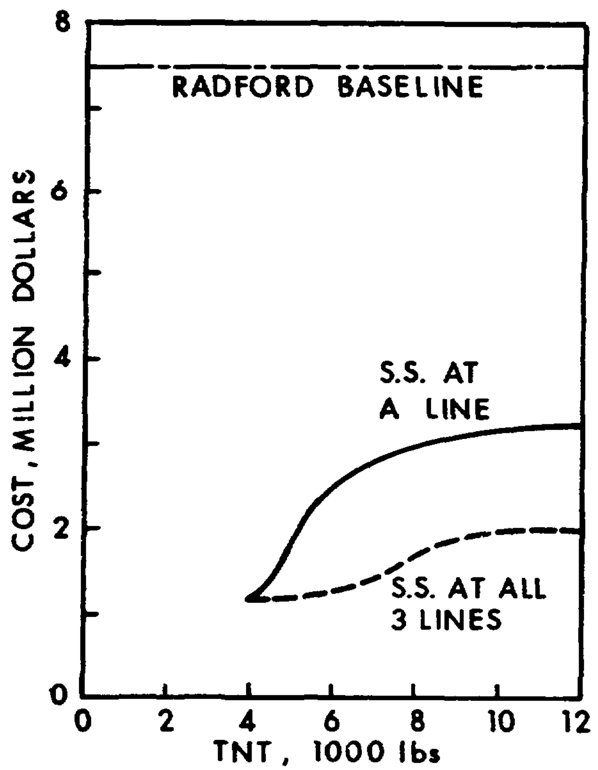

Figure 17. Damage Cost Estimates for Suppressive Structure with Effective Vent Area Ratio = 0.01

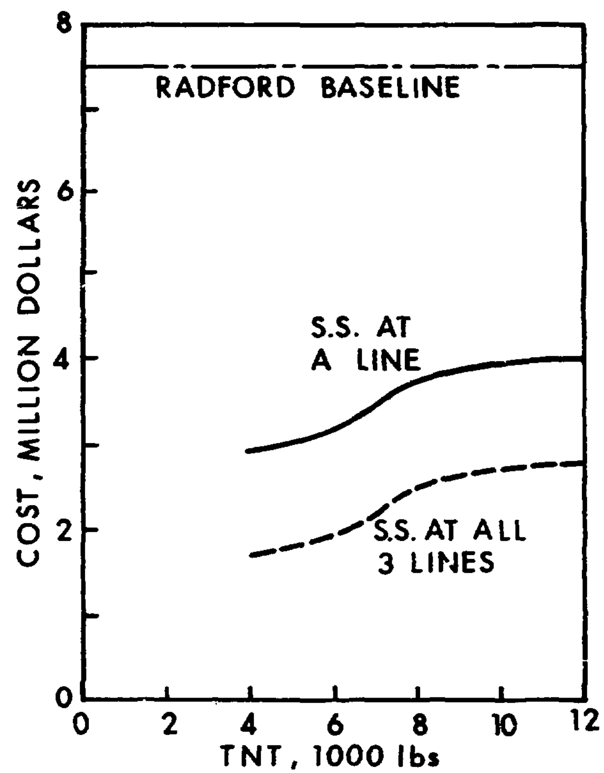

Figure 18. Damage Cost Estimates for Suppressive Structure with Effective Vent Area Ratio = 0.0194

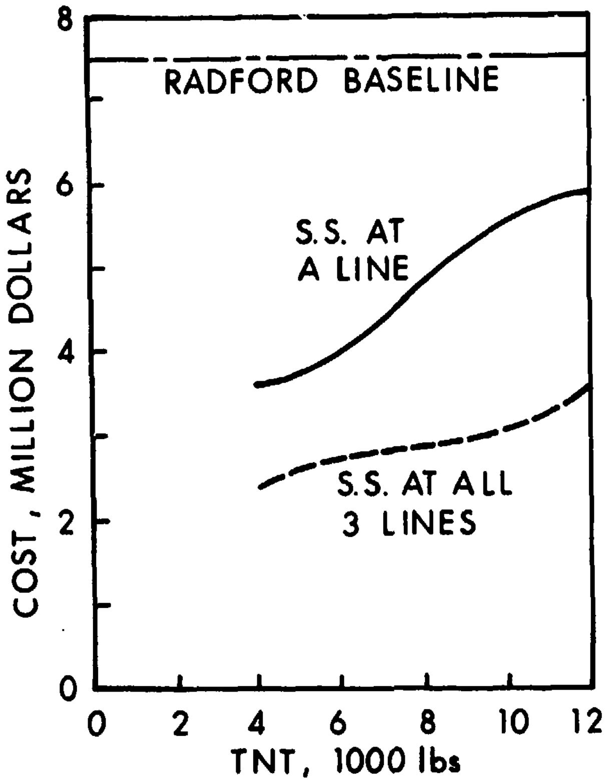

Figure 19. Damage Cost Estimates for Suppressive Structure with Effective Vent Area Ratio = 0.0373

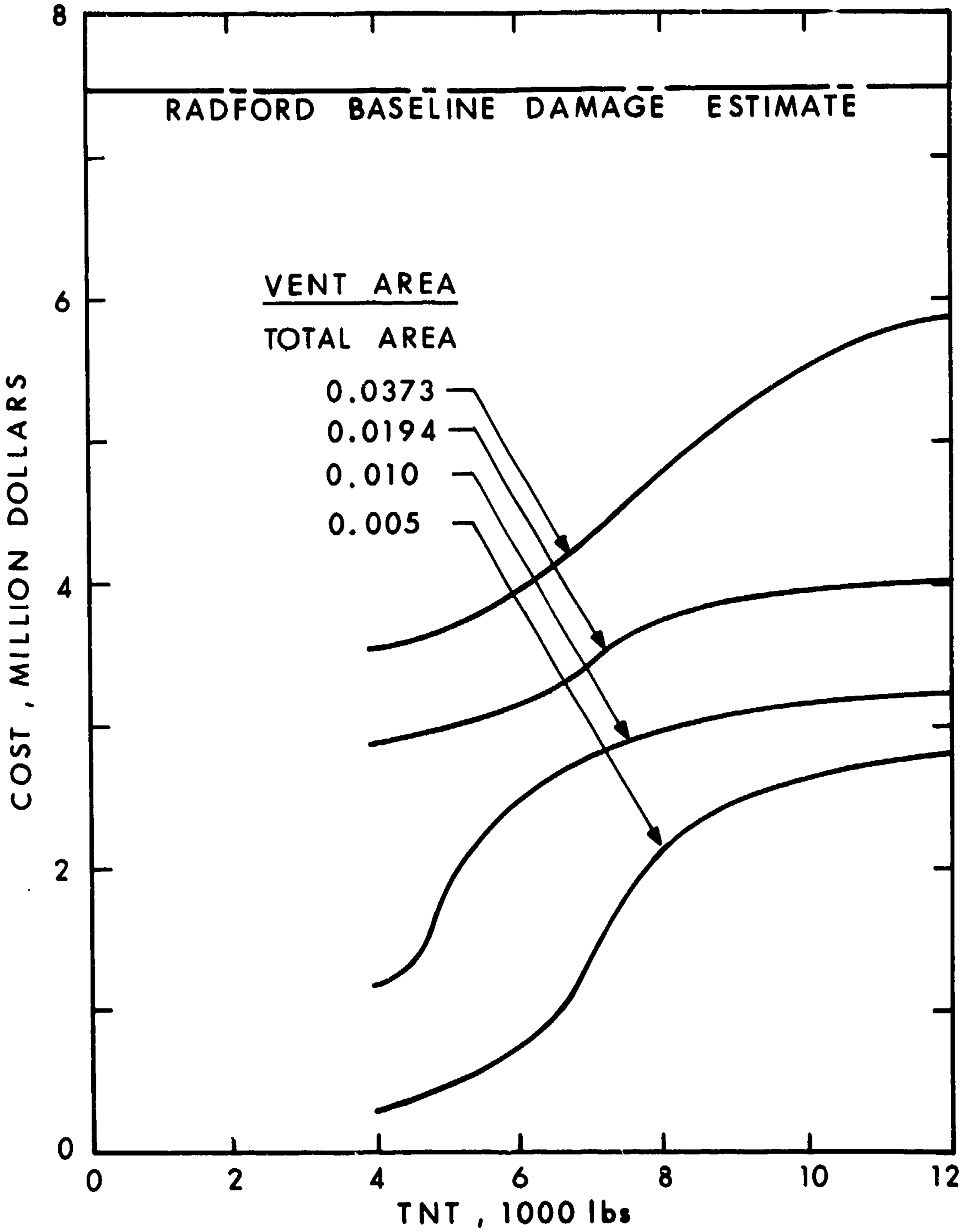

Figure 20. Influence of Suppressive Structure Vent Area to Total Area Ratio on Estimated Cost of Damage with Suppressive Structure Employed Only at A Line N&P Building

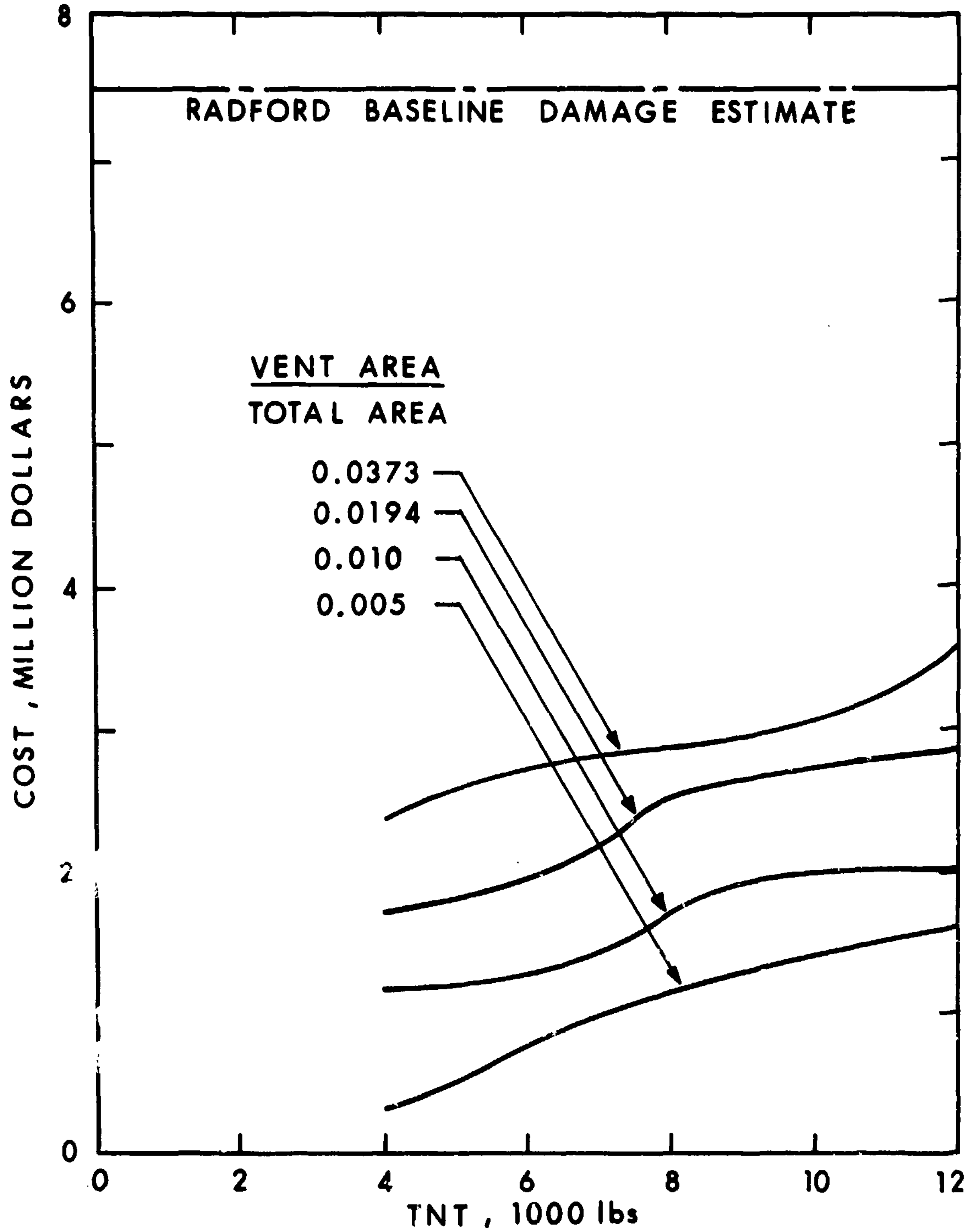

Figure 21. Influence of Suppressive Structure Vent Area to Total Area Ratio on Estimated Cost of Damage with Suppressive Structure Employed at All Three N&P Buildings

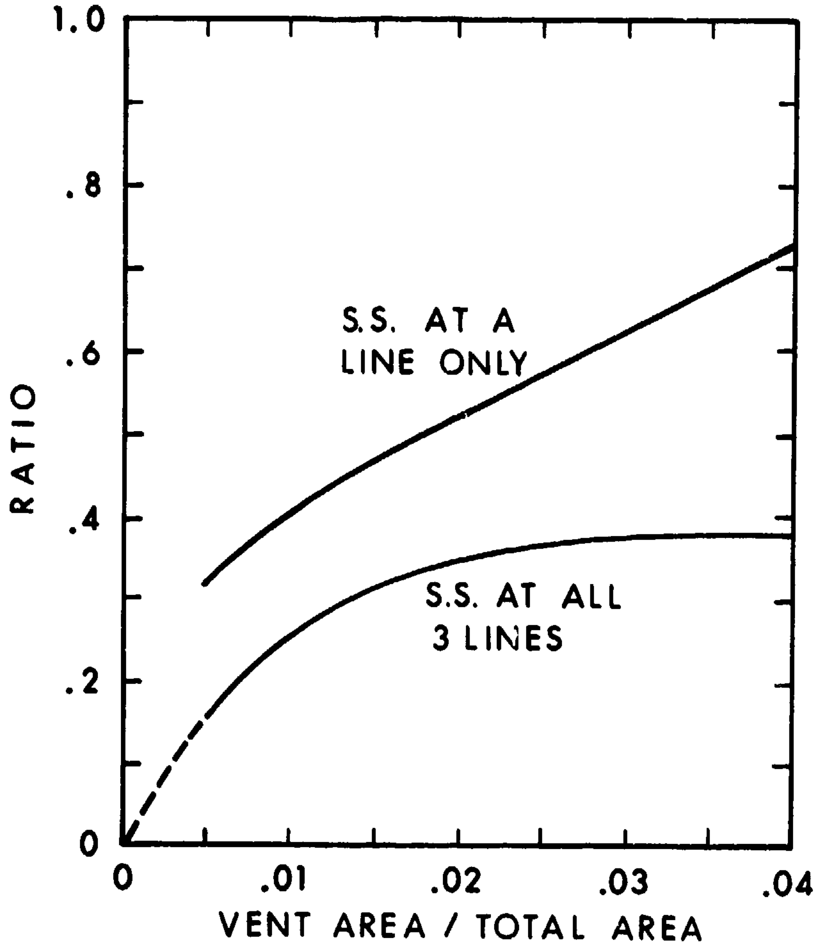

Figure 22. Ratio of Cost of Damage Incurred from Explosion of 8600 lb. TNT within a Suppressive Structure to the Cost of the Baseline Damage Caused by the 31 May 1974 Radford A Line TNT Accident

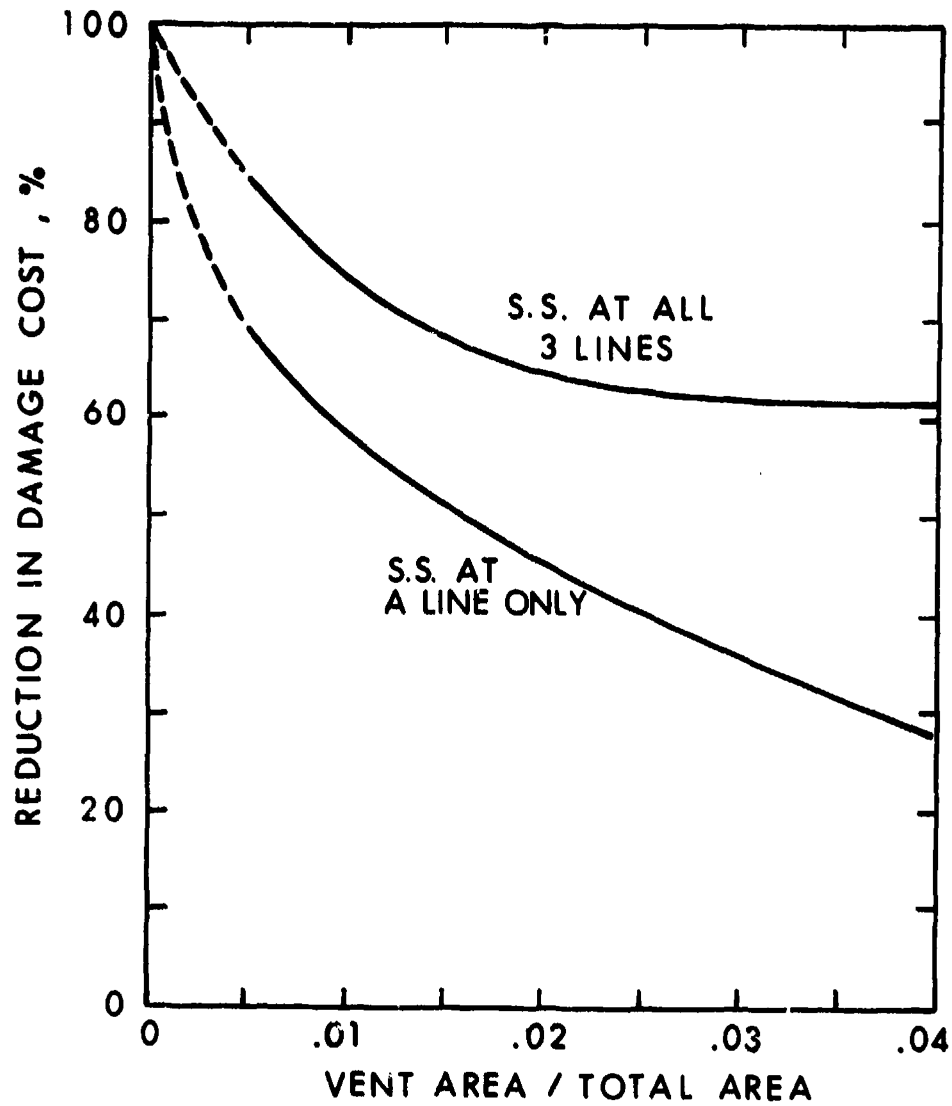

Figure 23. Reduction in the Cost of Damage Through the Use of Suppressive Structure-Type N&P Buildings Relative to the Baseline Damage Caused by the Radford TNT Accident

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